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Chapter 8

STARTING AND SPEED CONTROL METHODS

Starting refers to speed, current, and torque variations in an induction motor when fed directly or indirectly from a rather constant voltage and frequency local power grid.

A “stiff” local power grid would mean rather constant voltage even with large starting currents in the induction motors with direct full-voltage starting (5.5 to 5.6 times rated current is expected at zero speed at steady state). Full-starting torque is produced in this case and starting over notable loads is possible.

A large design KVA in the local power grid, which means a large KVA power transformer, is required in this case. For starting under heavy loads, such a large design KVA power grid is mandatory.

On the other hand, for low load starting, less stiff local power grids are acceptable. Voltage decreases due to large starting currents will lead to a starting torque, which decreases with voltage squared. As many local power grids are less stiff, for low starting loads, it means to reduce the starting currents, although in most situations even larger starting torque reduction is inherent for cage rotor induction machines.

For wound-rotor induction machines, additional hardware connected to the rotor brushes may provide even larger starting torque while starting currents are reduced. In what follows, various starting methods and their characteristics are presented. Speed control means speed variation with given constant or variable load torque. Speed control can be performed by either open loop (feed forward) or close loop (feedback). In this chapter, we will introduce the main methods for speed control and the corresponding steady state characteristics.

Transients related to starting and speed control are treated in Chapter 13. Close loop speed control methods are beyond the scope of this book as they are fully covered by literature presented by References 1 and 2

8.1 STARTING OF CAGE-ROTOR INDUCTION MOTORS

Starting of cage-rotor induction motors may be performed by:

- Direct connection to power grid
- Low voltage auto-transformer
- Star-delta switch connection
- Additional resistance (reactance) in the stator
- Soft starting (through static variacs)

8.1.1 Direct starting

Direct connection of cage-rotor induction motors to the power grid is used when the local power grid is off when rather large starting torques are required.

Typical variations of stator current and torque with slip (speed) are shown in Figure 8.1.

For single cage induction motors, the rotor resistance and leakage inductance are widely influenced by skin effect and leakage saturation. At start, the current is reduced and the torque is increased due to skin effect and leakage saturation.

In deep-bar or double-cage rotor induction motors, the skin effect is more influential as shown in Chapter 9. When the load torque is notable from zero speed on ($> 0.5 T_{cr}$) or the inertia is large ($J_{total} > 3J_{motor}$), the starting process is slower and the machine may be considered to advance from steady state to steady state until full-load speed is reached in a few seconds to minutes (in large motors).

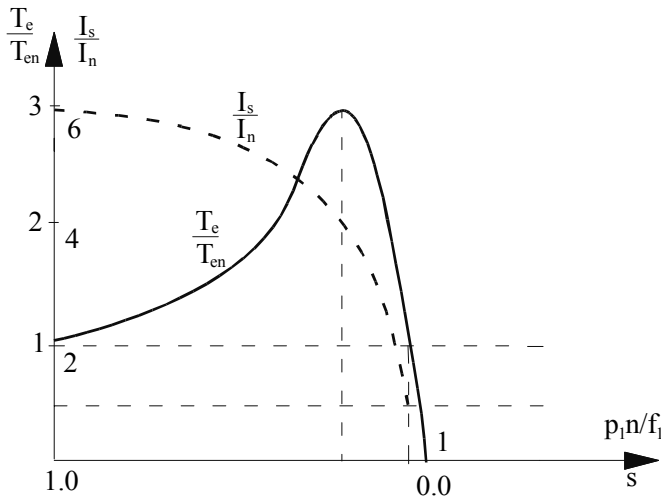


Figure 8.1 Current and torque versus slip (speed) in a single induction motions

If the induction motor remains at stall for a long time, the rotor and stator temperatures become too large, so there is a maximum stall time for each machine design.

On the other hand, for frequent start applications, it is important to count the rotor acceleration energy.

Let us consider applications with load torque proportional to squared speed (fans, ventilators). In this case we may, for the time being, neglect the load torque presence during acceleration. Also, a large inertia is considered and thus the steady state torque/speed curve is used.

$$\frac{J}{p_l} \cdot \frac{d\omega_r}{dt} \approx T_e(\omega_r); \omega_r = \omega_l(1 - S) \quad (8.1)$$

The rotor winding loss p_{cor} is

$$p_{\text{cor}} = S \cdot P_{\text{elm}} = S \cdot T_e \left(\frac{\omega_l}{P} \right) \quad (8.2)$$

with T_e from (8.1), the rotor winding losses W_{cor} are

$$\begin{aligned} W_{\text{cor}} &= \int_0^{t_s} \left(S \cdot T_e \cdot \frac{\omega_l}{p_l} \right) dt = \int_0^{t_r} \frac{J}{p_l} \cdot \frac{d\omega_r}{dt} \cdot \frac{\omega_l}{p_l} \cdot S dt \approx -\frac{J}{p_l^2} \int_1^0 \omega_l^2 \cdot S dS = \\ &= +\frac{J}{2} \left(\frac{\omega_l}{p_l} \right)^2; \quad S_{\text{initial}} = 1.0; \quad S_{\text{final}} = 0.0 \end{aligned} \quad (8.3)$$

On the other hand, the stator winding losses during motor acceleration under no load W_{cos} are:

$$W_{\text{cos}} = 3 \int_0^{t_s} I_s^2(S) R_s dt \approx 3 \int I_r'^2 \cdot R_r' \cdot \frac{R_s}{R_r'} dt \approx W_{\text{cor}} \cdot \frac{R_s}{R_r'} \quad (8.4)$$

Consequently, the total winding energy losses W_{co} are

$$W_{\text{co}} = W_{\text{cos}} + W_{\text{cor}} = \frac{J}{2} \left(\frac{\omega_l}{p_l} \right)^2 \left(1 + \frac{R_s}{R_r'} \right) \quad (8.5)$$

A few remarks are in order.

- The rotor winding losses during rotor acceleration under no load are equal to the rotor kinetic energy at ideal no-load speed
- Equation (8.5) tends to suggest that for given stator resistance R_s , a larger rotor resistance (due to skin effect) is beneficial
- The temperature transients during such frequent starts are crucial for the motor design, with (8.5) as a basic evaluation equation for total winding losses
- The larger the rotor attached inertia J , the larger the total winding losses during no load acceleration.

Returning to the starting current issue, it should be mentioned that even in a rather stiff local power grid a voltage drop occurs during motor acceleration, as the current is rather large. A 10% voltage reduction in such cases is usual.

On the other hand, with an oversized reactive power compensation capacitor, the local power grid voltage may increase up to 20% during low energy consumption hours.

Such a large voltage has an effect on voltage during motor starting in the sense of increasing both the starting current and torque.

Example 8.1 Voltage reduction during starting

The local grid power transformer in a small company has the data $S_n = 700$ KVA, secondary line voltage $V_{L2} = 440$ V (star connection), short circuit voltage $V_{SC} = 4\%$, $\cos\phi_{SC} = 0.3$. An induction motor is planned to be installed for direct starting. The IM power $P_n = 100$ kW, $V_L = 440$ V (star connection),

rated efficiency $\eta_n = 95\%$, $\cos\varphi_n = 0.92$, starting current $\frac{I_{\text{start}}}{I_n} = \frac{6.5}{1}$, and $\cos\varphi_{\text{start}} = 0.3$.

Calculate the transformer short circuit impedance, the motor starting current at rated voltage, and impedance at start. Finally determine the voltage drop at start, and the actual starting current in the motor.

Solution

First we have to calculate the rated transformer current in the secondary I_{2n}

$$I_{2n} = \frac{S_n}{\sqrt{3} \cdot V_{L2}} = \frac{700 \times 10^3}{\sqrt{3} \cdot 440} = 919.6 \text{ A} \quad (8.6)$$

The short circuit voltage V_{SC} corresponds to rated current

$$V_{SC2} = 0.04 \cdot \frac{V_{L2}}{\sqrt{3}} = I_{2n} |Z_{SC2}| \quad (8.8)$$

$$|Z_{SC2}| = \frac{0.04 \cdot 440}{\sqrt{3} \cdot 919.6} = 11.0628 \times 10^{-3} \Omega \quad (8.8)$$

$$R_{SC} = |Z_{SC}| \cos \varphi_{SC} = 11.0628 \cdot 10^{-3} \cdot 0.3 = 3.3188 \cdot 10^{-3} \Omega \quad (8.9)$$

$$X_{SC} = |Z_{SC}| \sin \varphi_{SC} = 11.0628 \cdot 10^{-3} \cdot \sqrt{1 - 0.3^2} = 10.5532 \cdot 10^{-3} \Omega$$

For the rated voltage, the motor rated current I_{sn} is

$$I_{sn} = \frac{P_n}{\sqrt{3} \eta_n \cos \varphi_n V_L} = \frac{100 \times 10^3}{\sqrt{3} \cdot 0.95 \cdot 0.92 \cdot 440} = 150.3 \text{ A} \quad (8.10)$$

The starting current is

$$I_{\text{start}} = 6.5 \times 150.3 = 977 \text{ A} \quad (8.11)$$

Now the starting motor impedance $Z_{\text{start}} = R_{\text{start}} + jX_{\text{start}}$ is

$$R_{\text{start}} = \frac{V_L}{\sqrt{3} I_{\text{start}}} \cos \varphi_{\text{start}} = \frac{440}{\sqrt{3} \cdot 977} \cdot 0.3 = 78.097 \times 10^{-3} \Omega \quad (8.12)$$

$$X_{\text{start}} = \frac{V_L}{\sqrt{3} I_{\text{start}}} \sin \varphi_{\text{start}} = \frac{440}{\sqrt{3} \cdot 977} \cdot \sqrt{1 - 0.3^2} = 0.24833 \Omega \quad (8.13)$$

Now the actual starting current in the motor/transformer I'_{start} is

$$\begin{aligned}
I'_{\text{start}} &= \frac{V_L}{\sqrt{3} |R_{\text{SC}} + R_{\text{start}} + j(X_{\text{SC}} + X_{\text{start}})|} = \\
&= \frac{440}{10^{-3} \sqrt{3} |3.3188 + 78.097 + j(10.5542 + 248.33)|} \\
&= 937 [0.3 + j0.954]
\end{aligned} \tag{8.14}$$

The voltage at motor terminal is:

$$\frac{V'_L}{V_L} = \frac{I'_{\text{start}}}{I_{\text{start}}} = \frac{937}{977} = 0.959 \tag{8.15}$$

Consequently the voltage reduction $\frac{\Delta V_L}{V_L}$ is

$$\frac{\Delta V_L}{V_L} = \frac{V_L - V'_L}{V_L} = 1.0 - 0.959 = 0.04094 \tag{8.16}$$

A 4.1% voltage reduction qualifies the local power grid as stiff for the starting of the newly purchased motor. The starting current is reduced from 977

A to 937 A, while the starting torque is reduced $\left(\frac{V'_L}{V_L}\right)^2$ times. That is, $0.959^2 \approx$

0.9197 times. A smaller KVA transformer and/or a larger shortcircuit transformer voltage would result in a larger voltage reduction during motor starting, which may jeopardize a safe start under heavy load.

Notice that high efficiency motors have larger starting currents so the voltage reduction becomes more severe. Larger transformer KVA is required in such cases.

8.1.2 Autotransformer starting

Although the induction motor power for direct starting has increased lately, for large induction motors (MW range) and not so stiff local power grids voltage, reductions below 10% are not acceptable for the rest of the loads and, thus, starting current reduction is mandatory. Unfortunately, in a cage rotor motor, this means a starting torque reduction, so reducing the stator voltage will reduce the stator current K_i times but the torque K_i^2 .

$$K_i = \frac{V_L}{V'_L} = \frac{I_L}{I'_L} = \sqrt{\frac{T_e}{T'_e}}; \quad I_s = \frac{V_L}{\sqrt{3} |Z_e(s)|} \tag{8.17}$$

because the current is proportional to voltage and the torque with voltage squared.

Autotransformer voltage reduction is adequate only with light high starting loads (fan, ventilator, pump loads).

A typical arrangement with three-phase power switches is shown on [Figure 8.2](#).

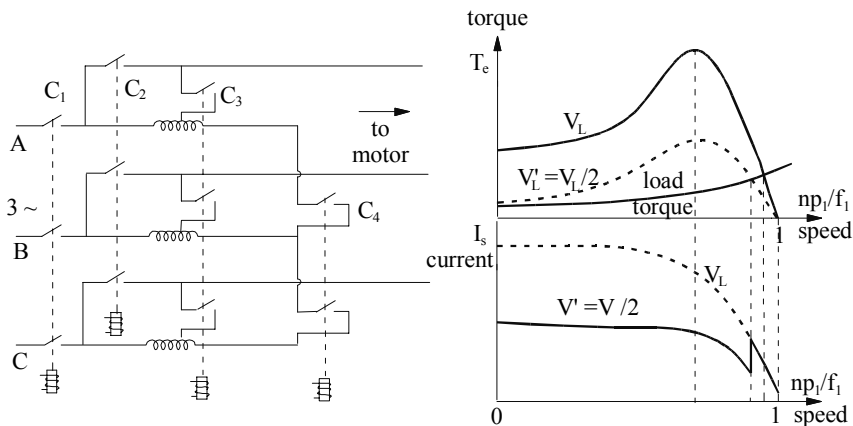


Figure.8.2 Autotransformer starting

Before starting, C_4 and C_3 are closed. Finally, the general switch C_1 is closed and thus the induction motor is fed through the autotransformer, at the voltage

$$V'_L \left(\frac{V'_L}{V_L} \cong 0.5, 0.65, 0.8 \right)$$

To avoid large switching current transients when the transformer is bypassed, and to connect the motor to the power grid directly, first C_4 is opened and C_2 is closed with C_3 still closed. Finally, C_3 is opened. The transition should occur after the motor accelerated to almost final speed or after a given time interval for start, based on experience at the commissioning place. Autotransformers are preferred due to their smaller size, especially with $\frac{V'_L}{V_L} = 0.5$ when the size is almost halved.

8.1.3 Wye-delta starting

In induction motors that are designed to operate with delta stator connection it is possible, during starting, to reduce the phase voltage by switching to wye connection ([Figure 8.3](#)).

During wye connection, the phase voltage V_s becomes

$$V_s = \frac{V_L}{\sqrt{3}} \quad (8.18)$$

so the phase current, for same slip, I_{sY} , is reduced $\sqrt{3}$ times

$$I_{s\Delta} = \frac{I_{s\Delta}}{\sqrt{3}} \quad (8.19)$$

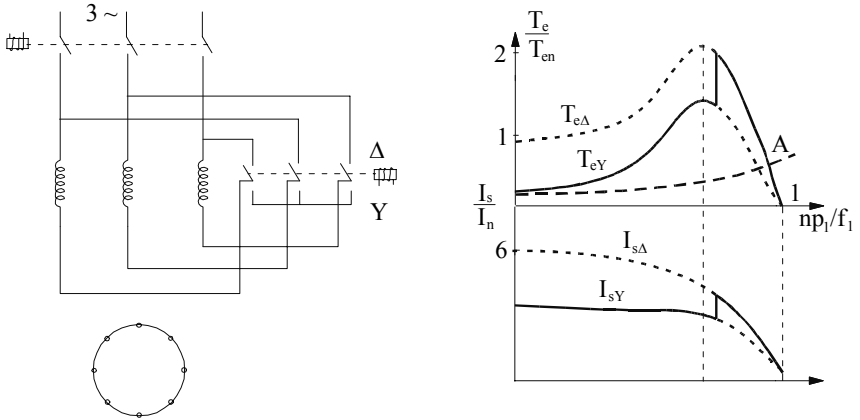


Figure 8.3 Wye-delta starting

Now the line current in Δ connection $I_{L\Delta}$ is

$$I_{L\Delta} = \sqrt{3}I_{s\Delta} = 3I_{sY} \quad (8.20)$$

so the line current is three times smaller for wye connection. The torque is proportional to phase voltage squared

$$\frac{T_{e\Delta}}{T_{eY}} = \left(\frac{V_{sY}}{V_L} \right)^2 = \frac{1}{3} \quad (8.21)$$

therefore, the wye-delta starting is equivalent to an $\frac{\sqrt{3}}{1}$ reduction of phase voltage and a 3 to 1 reduction in torque. Only low load torque (at low speeds) and mildly frequent start applications are adequate for this method.

A double-throw three-phase power switch is required and notable transients are expected to occur when switching from wye to delta connection takes place.

An educated guess in starting time is used to figure when switching is to take place.

The series resistance and series reactance starting methods behave in a similar way as voltage reduction in terms of current and torque. However, they are not easy to build especially in high voltage (2.3 kV, 4 kV, 6 kV) motors. At the end of the starting process they have to be shortcircuited. With the advance of softstarters, such methods are used less and less frequently.

8.1.4 Softstarting

We use here the term softstarting for the method of a.c. voltage reduction through a.c. voltage controllers called softstarters.

In numerous applications such as fans, pumps, or conveyors, softstarters are now common practice when speed control is not required.

Two basic symmetric softstarter configurations are shown in [Figure 8.4](#). They use thyristors and enjoy natural commutation (from the power grid). Consequently, their cost is reasonably low to be competitive.

In small (sub kW) power motors, the antiparallel thyristor group may be replaced by a triac to cut costs.

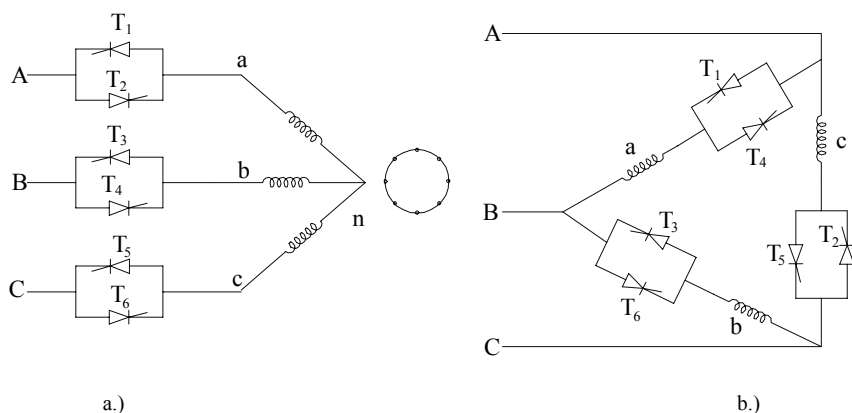


Figure 8.4 Softstarters for three-phase induction motors: a.) wye connection, b.) delta connection

Connection a.) in [Figure 8.4](#) may also be used with delta connection and this is why it became a standard in the marketplace.

Connection b.) in [Figure 8.4](#) reduces the current rating of the thyristor by $\sqrt{3}$ in comparison with connection a.). However, the voltage rating is basically the same as the line voltage, and corresponds to a faulty condition when thyristors in one phase remain on while all other phases would be off.

To apply connection b.), both phase ends should be available, which is not the case in many applications.

The 6 thyristors in [Figure 8.4 b.\)](#) are turned on in the order $T_1, T_2, T_3, T_4, T_5, T_6$ every 60° . The firing angle α is measured with respect to zero crossing of V_{an} ([Figure 8.5](#)). The motor power factor angle is φ_{10} .

The stator current is continuous if $\alpha < \varphi_1$ and discontinuous ([Figure 8.5](#)) if $\alpha > \varphi_1$.

As the motor power factor angle varies with speed ([Figure 8.5](#)), care must be exercised to keep $\alpha > \varphi_1$ as a current (and voltage) reduction for starting is required.

So, besides voltage, current fundamentals, and torque reductions, the soft starters produce notable voltage and current low-order harmonics. Those harmonics pollute the power grid and produce additional losses in the motor. This is the main reason why softstarters do not produce notable energy savings when used to improve performance at low loads by voltage reduction. [3]

However, for light load starting, they are acceptable as the start currents are reduced. The acceleration into speed time is increased, but it may be programmed (Figure 8.6).

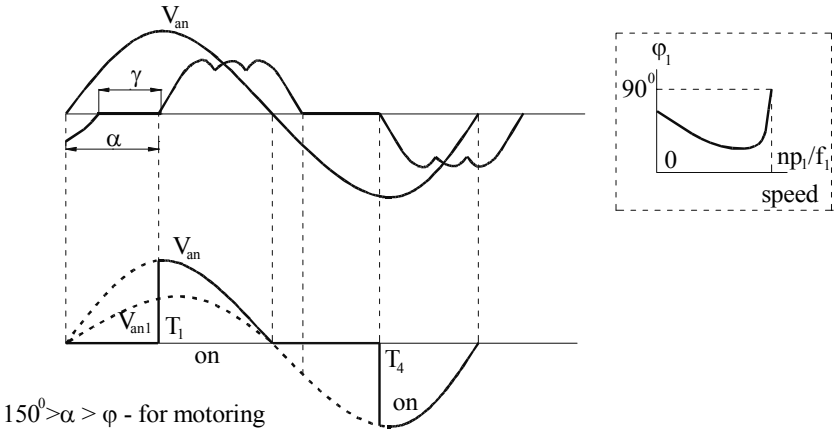


Figure 8.5 Softstarter phase voltage and current

During starting, either the stator current or the torque may be controlled. After the start ends, the soft starter will be isolated and a bypass power switch takes over. In some implementations only a short-circuiting (bypass) power switch is closed after the start ends and the softstarter command circuits are disengaged (Figure 8.7). Dynamic braking is also performed with softstarters. The starting current may be reduced to twice rated current or more.

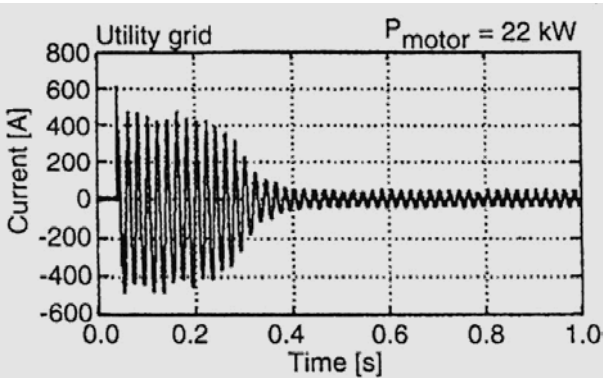
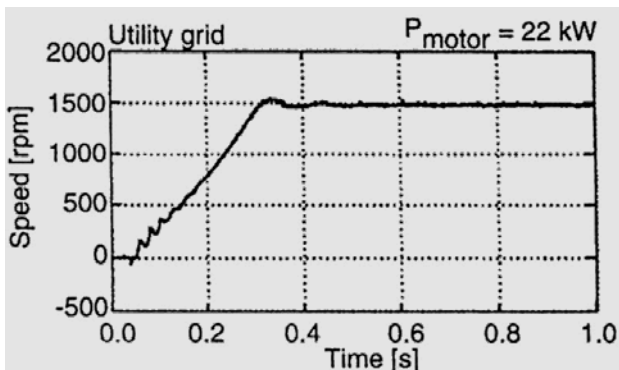
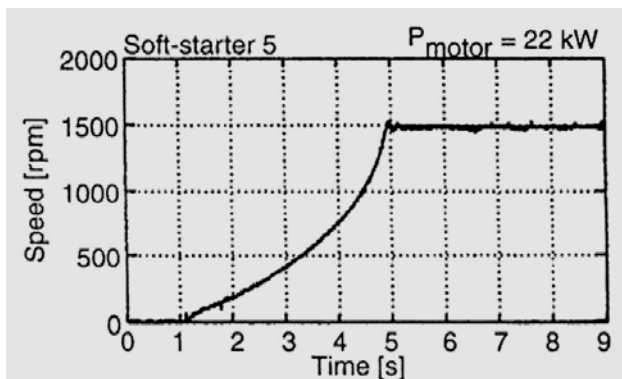
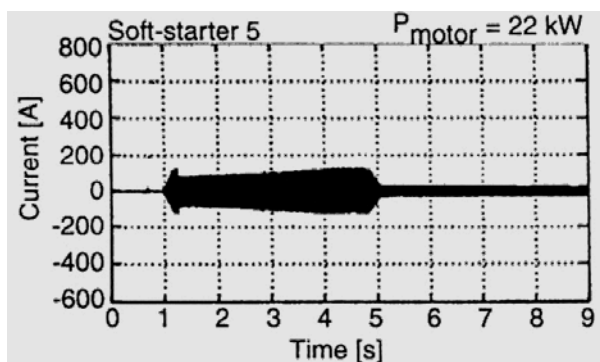


Figure 8.6 Start under no load of a 22 kW motor
a) direct starting; b) softstarting (continued)



a.)



b.)

Figure 8.6 (continued)

8.2 STARTING OF WOUND-ROTOR INDUCTION MOTORS

A wound-rotor induction motor is built for heavy load frequent starts and (or) limited speed control motoring or generating at large power loads (above a few hundred kW).

Here we insist on the classical starting method used for such motors: variable resistance in the rotor circuit (Figure 8.8). As discussed in the previous chapter, the torque/speed curve changes with additional rotor resistance in terms of critical slip S_k , while the peak (breakdown) torque remains unchanged (Figure 8.8.b.).

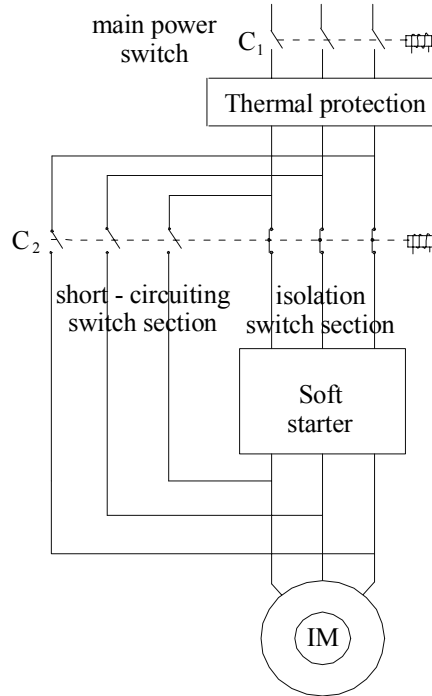


Figure 8.7 Softstarter with isolation and short-circuiting power switch C_2

$$s_K = \frac{C_1(R'_r + R'_{ad})}{\sqrt{R_s^2 + (X_{sl} + C_1 X'_{rl})^2}} \quad (8.22)$$

$$T_{ek} = \frac{3p_1}{2C_1} \frac{V_s^2}{\omega_1} \cdot \frac{1}{R_1 \pm \sqrt{R_s^2 + (X_{sl} + C_1 X'_{rl})^2}}$$

As expected, the stator current, for given slip, also decreases with R'_{ad} increasing (Figure 8.8 c.). It is possible to start ($S'' = 1$) with peak torque by providing $S_K'' = 1.0$. When R'_{ad} increases, the power factor, especially at high slips, improves the torque/current ratio. The additional losses in R'_{ar} make this method poor in terms of energy conversion for starting or sustained low-speed operation.

However, the peak torque at start is an extraordinary feature for heavy starts and this feature has made the method popular for driving elevators or overhead cranes.

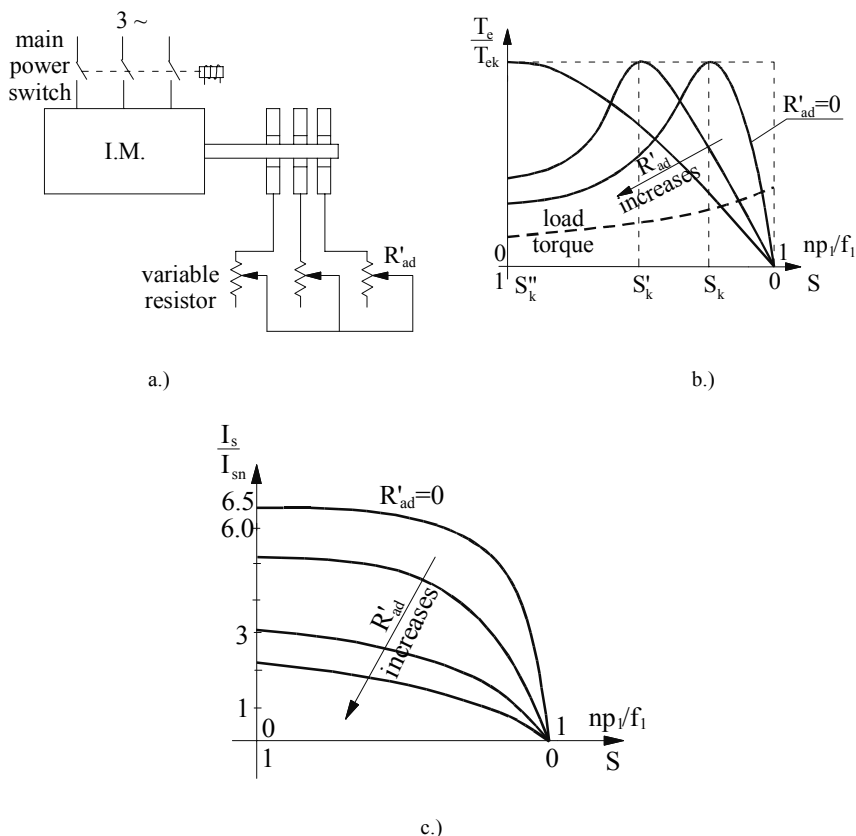


Figure 8.8 Starting through additional rotor resistance R'_{ad}
a.) general scheme, b.) torque/speed, c.) current/speed

There are a few ways to implement the variable rotor resistance method as shown in Figure 8.9 a,b,c.

The half-controlled rectifier and the diode-rectifier-static switch methods (Figure 8.8 a,b) allow for continuous stator (or rotor) current close loop control during starting. Also, only a fixed resistance is needed.

The diode rectifier-static-switch method implies a better power factor and lower stator current harmonics but is slightly more expensive.

A low cost solution is shown in Figure 8.9 c, where a three-phase pair of constant resistances and inductances lead to an equivalent resistance R_{oe} (Figure 8.9 c), which increases when slip increases (or speed decreases).

The equivalent reactance of the circuit decreases with slip increases. In this case, there is no way to intervene in controlling the stator current unless the inductance L_0 is varied through a d.c. coil which controls the magnetic saturation in the coil laminated magnetic core.

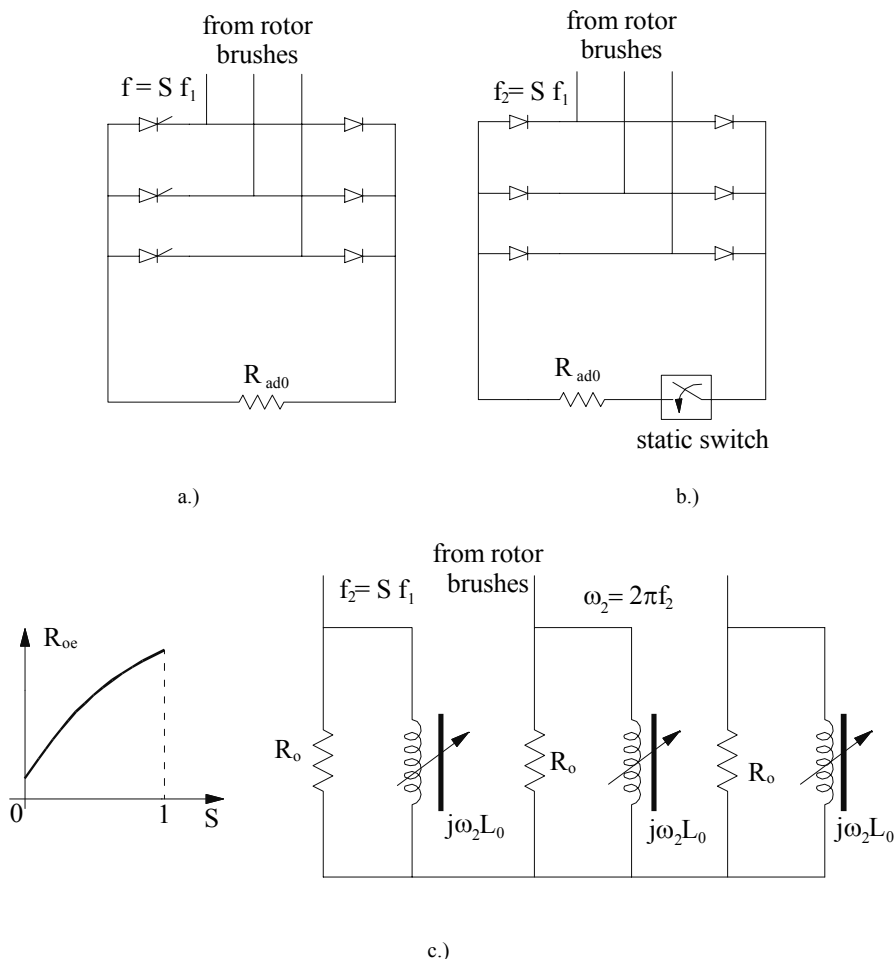


Figure 8.9 Practical implementations of additional rotor resistance
a.) with half-controlled rectifier; b.) with diode rectifier and static switch; c.) with self-adjustable resistance

8.3 SPEED CONTROL METHODS FOR CAGE-ROTOR INDUCTION MOTORS

Speed control means speed variation under open loop (feedforward) or close loop conditions. We will discuss here only the principles and steady-state characteristics of speed control methods.

For cage-rotor induction motors, all speed control methods have to act on the stator windings as only they are available.

To start, here is the speed/slip relationship.

$$n = \frac{f_1}{p_1}(1 - S) \quad (8.23)$$

Equation (8.23) suggests that the speed may be modified through

- Slip S variation: through voltage reduction
- Pole number $2p_1$ change: through pole changing windings
- Frequency f_1 control: through frequency converters

8.3.1 The voltage reduction method

When reducing the stator phase (line) voltage through an autotransformer or an a.c. voltage controller as inferred from (8.22), the critical slip s_K remains constant, but the peak (breakdown) torque varies with voltage V_s squared (Figure 8.10).

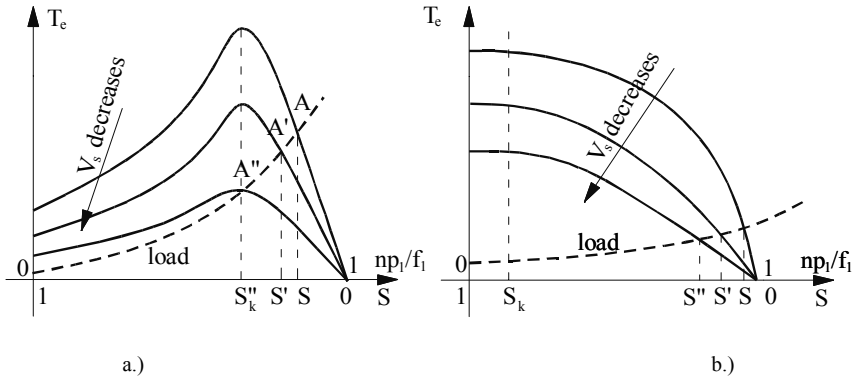


Figure 8.10 Torque versus speed for different voltage levels V_s

a.) standard motor: $S_K = 0.04 - 0.10$

b.) high rotor resistance (solid iron) rotor motor $S_K > 0.7 - 0.8$

$$T_e = f(S) \cdot V_s^2 \quad (8.24)$$

The speed may be varied downward until the critical slip speed n_K is reached.

$$n_K = \frac{f_1}{p_1}(1 - S_K) \quad (8.25)$$

In standard motors, this means an ideal speed control range of

$$(n_1 - n_K)/n_1 = S_K < 0.1 = 10\% \quad (8.26)$$

On the contrary, in high rotor resistance rotor motors, such as solid rotor motors where the critical slip is high, the speed control range may be as high as 100%.

However, in all cases, when increasing the slip, the rotor losses increase accordingly, so the wider the speed control range, the poorer the energy conversion ratio.

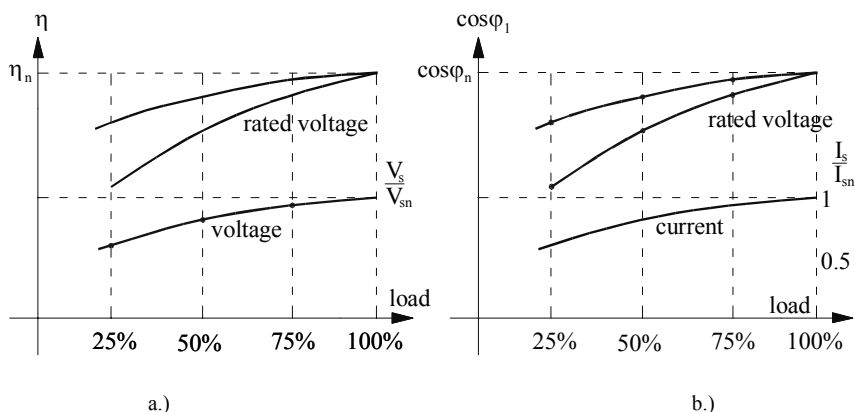


Figure 8.11 Performance versus load for reduced voltage
a.) voltage V_s/V_{sn} and efficiency η
b.) $\cos \phi_1$ and stator current

Finally, a.c. voltage controllers (soft starters) have been proposed to reduce voltage, when the load torque decreases, to reduce the flux level in the machine and thus reduce the core losses and increase the power factor and efficiency while stator current also decreases.

The slip remains around the rated value. Figure 8.11. show a qualitative illustration of the above claims.

The improvement in performance at light loads, through voltage reduction, tends to be larger in low power motors (less than 10 kW) and lower for larger power levels. [3] In fact, above 50% load the overall efficiency decreases due to significant soft starter losses.

For motor designs dedicated to long light load operation periods, the efficiency decreases only 3 to 4% from 100% to 25% load and, thus, reduced voltage by soft starters does not produce significant performance improvements. In view of the above, voltage reduction has very limited potential for speed control.

8.3.2 The pole-changing method.

Changing the number of poles, $2p_1$, changes the ideal no-load speed $n_1 = f_1/p_1$ accordingly. In Chapter 4, we discussed pole-changing windings and their connections of phases to produce constant power or constant torque for the two different pole numbers $2p_2$ and $2p_1$ (Figure 8.12).

The IM has to be sized carefully for the largest torque conditions and with careful checking for performance for both $2p_1$ and $2p_2$ poles.

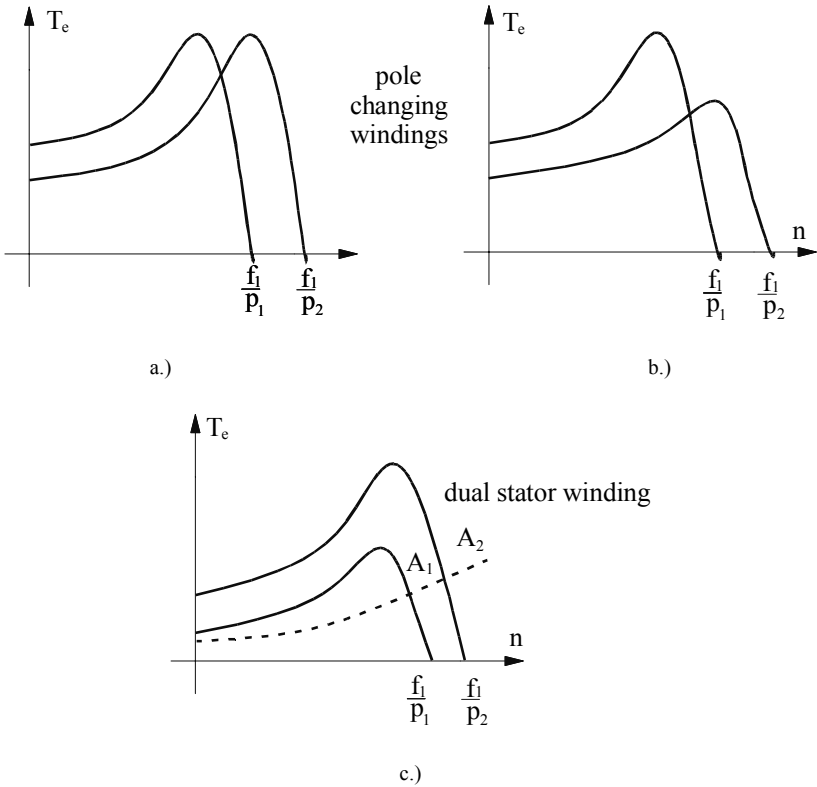


Figure 8.12 Pole-changing torque/speed curves
a.) constant torque; b.) constant power; c.) dual winding

Switching from $2p_2$ to $2p_1$ and back in standard pole-changing ($p_2/p_1 = 2$ Dahlander) windings implies complicated electromechanical power switches.

Better performance, new pole-changing windings (Chapter 4) that require only 2 single throw power switches have been proposed recently.

For applications where the speed ratio is $3/2$, $4/3$, $6/4$, etc. and the power drops dramatically for the lower speed (wind generators), dual windings may be used. The smaller power winding will occupy only a small part of slot area. Again, only two power switches are required-the second one of notably smaller power rating.

Pole-changing windings are also useful for wide speed range $\omega_{\max}/\omega_b > 3$ power induction motor drives (spindle drives or electric (or hybrid) automobile electric propulsion). This solution is a way to reduce motor size for $\omega_{\max}/\omega_b > 3$.

8.4 VARIABLE FREQUENCY METHODS

When changing frequency f_1 , the ideal no-load speed $n_1=f_1/p_1$ changes and so does the motor speed for given slip.

Frequency static converters are capable of producing variable voltage and frequency, V_s , f_1 . A coordination of V_s with f_1 is required.

Such a coordination may be “driven” by an optimization criterion or by flux linkage control in the machine to secure fast torque response.

The various voltage-frequency relationships may be classified into 4 main categories:

- V/f scalar control
- Rotor flux vector control
- Stator flux vector control
- Direct torque and flux control

Historically, the V/f scalar control was first introduced and is used widely today for open loop speed control in driving fans, pumps, etc., which have the load torque dependent on speed squared, or more. The method is rather simple, but the torque response tends to be slow.

For high torque response performance, separate flux and torque control much like in a d.c. machine, is recommended. This is called vector control.

Either rotor flux or stator flux control is performed. In essence, the stator current is decomposed into two components. One is flux producing while the other one is torque producing. This time the current or voltage phase and amplitude and frequency are continuously controlled. Direct torque and flux control (DTFC) [2] shows similar performance.

Any torque/speed curve could thus be obtained as long as voltage and current limitations are met. Also very quick torque response, as required in servodrives, is typical for vector control.

All these technologies are now enjoying very dynamic markets worldwide.

8.4.1 V/f scalar control characteristics

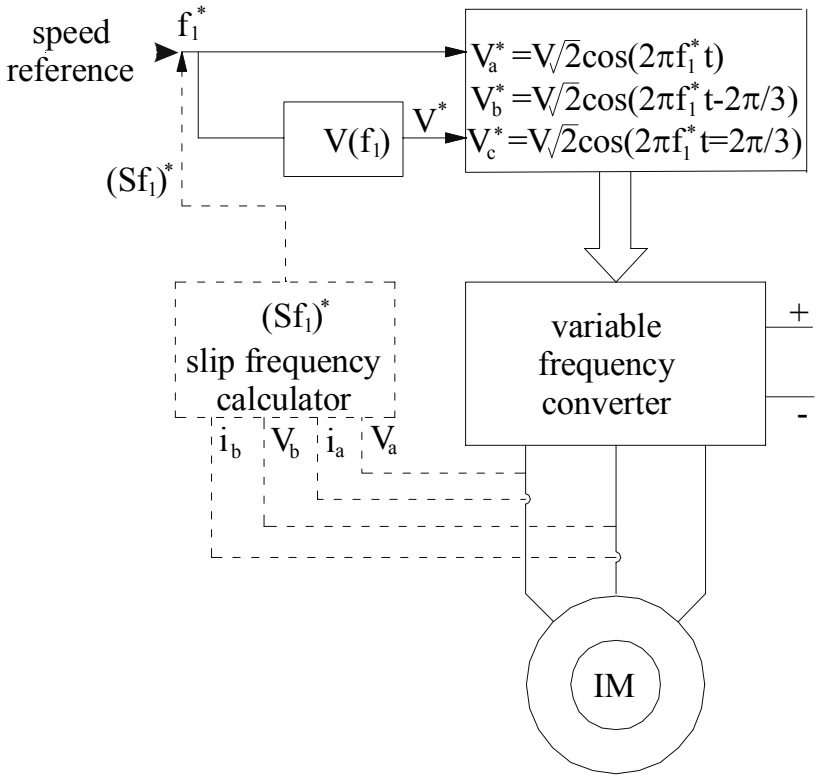
The frequency converter, which supplies the motor produces sinusoidal symmetrical voltages whose frequency is ramped for starting. Their amplitude is related to frequency by a certain relationship of the form

$$V = V_0 + K_0(f_1) \cdot f_1 \quad (8.27)$$

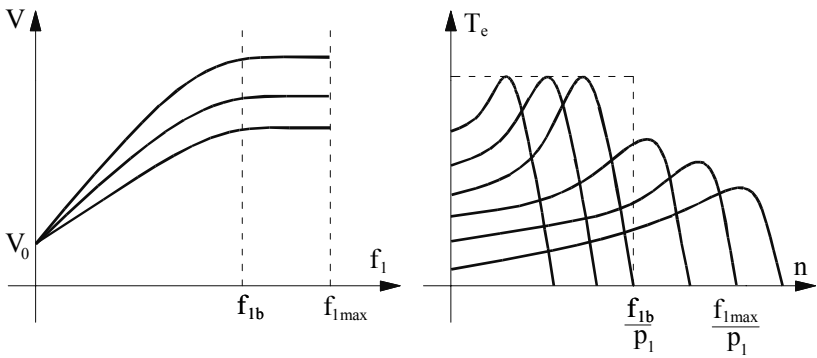
V_0 is called the voltage boost destined to cover the stator resistance voltage at low frequency (speed).

Rather simple $K_0(f_1)$ functions are implemented into digitally controlled variable frequency converters (Figure 8.13).

As seen in (Figure 8.13 a), a slip frequency compensator may be added to reduce speed drop with load (Figure 8.14).



a.)



b.)

c.)

Figure 8.13 V/f speed control
a) structural diagram b) V/f relationship c) torque/speed curve

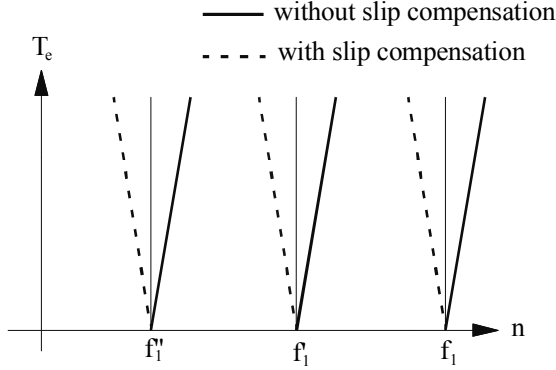


Figure 8.14 Torque/speed curves with slip compensation

Safe operation is provided above $f_{\min} = 3$ Hz as torque response is rather slow (above 20 milliseconds).

Example 8.2 V/f speed control

An induction motor has the following design data: $P_n = 10$ kW, $V_{Ln} = 380$ V (Y), $f_{lb} = 50$ Hz, $\eta_n = 0.92$, $\cos\phi_n = 0.9$, $2p_1 = 4$, $I_{\text{start}}/I_n = 6/1$, $I_0/I_{sn} = 0.3$, $p_{\text{mec}} = 0.015P_n$, $p_{\text{add}} = 0.015P_n$; core losses are neglected and $R_s = R'_r$ and $X_{sl} = X'_{rl}$. Such data are known from the manufacturer. Let us calculate: rated current, motor parameters R_s , X_{sl} , X_{lm} , critical slip S_K and breakdown torque T_{eK} at f_{lb} , and $f_{l\max}$ for rated voltage; voltage for critical slip S_K and minimum frequency $f_{l\min} = 3$ Hz to provide rated breakdown torque.

Find the voltage boost V_0 for linear V/f dependence up to base speed.

Solution

$$f_{lb} = 50 \text{ Hz}$$

Based on the efficiency expression

$$\eta_n = \frac{P_n}{\sqrt{3} V_L I_{sn} \cos \phi_n} \quad (8.28)$$

The rated current

$$I_{sn} = \frac{10000}{\sqrt{3} \cdot 0.92 \cdot 380 \cdot 0.9} = 18.37 \text{ A}$$

The rotor and stator winding losses $p_{\cos} + p_{\text{cor}}$ are

$$p_{\cos} + p_{\text{cor}} = \frac{P_n}{\eta_n} - P_n - p_{\text{mec}} - p_{\text{add}} \quad (8.29)$$

$$p_{\cos} + p_{\text{cor}} = 10000 \left(\frac{1}{0.92} - 1 - 0.015 - 0.015 \right) = 569.56 \text{ W}$$

Now:

$$p_{\cos} + p_{\text{cor}} = 3R_s I_{\text{sn}}^2 + 3R_r I_{\text{rn}}^2 \quad (8.30)$$

$$I'_{\text{rn}} \approx \sqrt{I_{\text{sn}}^2 - I_{0\text{n}}^2} = 18.37 \cdot \sqrt{1 - 0.3^2} = 17.52 \text{ A} \quad (8.31)$$

From (8.30) and (8.31)

$$R_s = R_r = \frac{569.56}{3 \cdot (18.37^2 + 17.52^2)} = 0.4316 \Omega$$

Neglecting the skin effect,

$$X_{\text{sc}} = X_{\text{sl}} + X'_{\text{rl}} \approx \sqrt{\left(\frac{V_{\text{sn}}}{I_{\text{start}}} \right)^2 - (R_s + R'_r)^2} = \sqrt{\left(\frac{380/\sqrt{3}}{6 \cdot 18.37} \right)^2 - 0.8632^2} = 1.80 \Omega \quad (8.32)$$

Therefore,

$$X_{\text{sl}} = X'_{\text{rl}} = 0.9 \Omega$$

The critical slip S_K (8.22) and breakdown torque T_{eK} (8.22) are, for $f_1 = f_{1\text{b}}$
= 50 Hz,

$$(S_K)_{50\text{Hz}} = \frac{R'_r}{\sqrt{R_s^2 + X_{\text{sc}}^2}} = \frac{0.4316}{\sqrt{0.4316^2 + 1.8^2}} = 0.233 \quad (8.33)$$

$$\begin{aligned} (T_{\text{eK}})_{50\text{Hz}} &= \frac{3p_1}{2} \frac{(V_{\text{Ln}}/\sqrt{3})^2}{2\pi f_{1\text{b}}} \cdot \frac{1}{R_s + \sqrt{R_s^2 + X_{\text{sc}}^2}} = \\ &= 3 \cdot \frac{2}{2} \cdot \frac{220^2}{2\pi 50} \cdot 0.4378 = 202.44 \text{ Nm} \end{aligned} \quad (8.34)$$

for $f_{1\text{max}} = 100 \text{ Hz}$

$$(S_K)_{100\text{Hz}} = \frac{R'_r}{\sqrt{R_s^2 + X_{\text{sc}}^2 \cdot \left(\frac{f_{1\text{max}}}{f_{1\text{b}}} \right)^2}} = \frac{0.4316}{\sqrt{0.4316^2 + 1.8^2 \cdot \left(\frac{100}{50} \right)^2}} = 0.119 \quad (8.35)$$

$$\begin{aligned}
 (T_{eK})_{100\text{Hz}} &= \frac{3p_l}{2} \frac{(V_{Ln}/\sqrt{3})^2}{2\pi f_{l\max}} \cdot \frac{1}{R_s + \sqrt{R_s^2 + \left(X_{sc} \cdot \frac{f_{l\max}}{f_{lb}}\right)^2}} = \\
 &= 3 \cdot \frac{2}{2} \cdot \frac{220^2}{2\pi 100} \cdot \frac{1}{0.4316 + \sqrt{0.4316^2 + 1.8^2 \left(\frac{100}{50}\right)^2}} = 113.97 \text{ Nm}
 \end{aligned} \quad (8.36)$$

$$(S_K)_{f_{l\min}} = \frac{R'_r}{\sqrt{R_s^2 + \left(X_{sc} \cdot \frac{f_{l\min}}{f_{lb}}\right)^2}} = \frac{0.4316}{\sqrt{0.4316^2 + \left(1.8 \cdot \frac{3}{50}\right)^2}} = 0.97! \quad (8.37)$$

From (8.36), written for $f_{l\min}$ and $(T_{eK})_{50\text{Hz}}$, the stator voltage $(V_s)_{3\text{Hz}}$ is

$$\begin{aligned}
 (V_s)_{3\text{Hz}} &= \sqrt{\frac{2(T_{eK})_{50\text{Hz}} \cdot 2\pi f_{l\min} \left(\sqrt{R_s^2 + \left(X_{sc} \cdot \frac{f_{l\min}}{f_{lb}}\right)^2} + R_s \right)}{3 \cdot p_l}} \\
 &= \sqrt{\frac{2 \cdot 202.44 \cdot 2\pi \cdot 3}{3 \cdot 2} \left(\sqrt{0.4316^2 + \left(1.8 \cdot \frac{3}{50}\right)^2} + 0.4316 \right)} = 33.38 \text{ V}
 \end{aligned} \quad (8.38)$$

And, according to (8.27), the voltage increases linearly with frequency up to base (rated) frequency $f_{lb} = 50 \text{ Hz}$,

$$\begin{aligned}
 33.38 &= V_0 + K_0 \cdot 3 \\
 220 &= V_0 + K_0 \cdot 50
 \end{aligned} \quad (8.39)$$

$$K_0 = 3.97 \text{ V/Hz}; V_0 = 21.47 \text{ V}$$

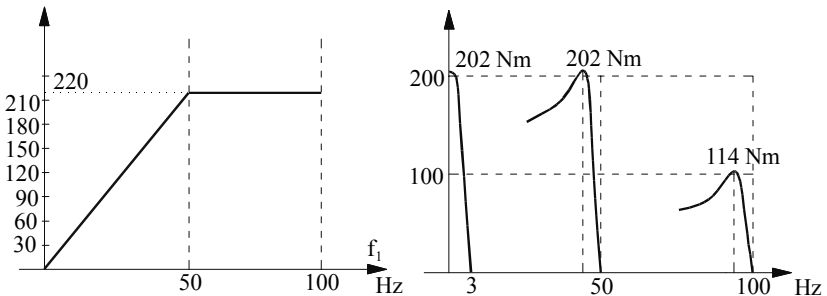


Figure 8.15 V/f and peak torque for V/f control

The results are synthesized on [Figure 8.15](#). Toward minimum frequency $f_{lmin} = 3$ Hz, the neglect of magnetizing reactance branch in the critical slip calculation may produce notable errors.

A check of stator current and torque at $(S_K)_{3Hz} = 0.97$, $V_{sn} = 33.38$ V, $f_{lmin} = 3$ Hz is recommended. This aspect suggests that assigning a value for voltage boost V_0 is a sensitive issue.

Any variation of parameters due to temperature (resistances) and magnetic saturation (inductances) may lead to serious stability problems. This is the main reason why V/f control method, though simple, is to be used only with light load start applications.

8.4.2 Rotor flux vector control

As already mentioned, when firm starting or stable low speed performance is required, vector control is needed. To start, let us reconsider the IM equations for steady state (Chapter 7, paragraph 7.10, Equations (7.97) and (7.98)).

$$\begin{aligned} \underline{I}_s R_s - V_s &= -j\omega_l \underline{\Psi}_s \\ \underline{I}'_r R'_r &= -j\omega_l S \underline{\Psi}_r \end{aligned} \quad \text{for } V'_r = 0 \text{ (cage rotor)} \quad (8.40)$$

Also from (7.95),

$$\underline{\Psi}_s = \frac{L_{lm}}{L'_r} \cdot \underline{\Psi}'_r + L_{sc} \underline{I}_s; \underline{I}'_r = \frac{\underline{\Psi}'_r}{L'_r} - \frac{L_{lm}}{L'_r} \cdot \underline{I}_s \quad (8.41)$$

The torque (7.100) is,

$$T_e = 3p_l \Psi'_r I'_r \quad (8.42)$$

It is evident in (8.40) that for steady state in a cage rotor IM, the rotor flux and current per equivalent phase are phase-shifted by $\pi/2$. This explains the torque formula (8.42) which is very similar to the case of a d.c. motor with separate excitation.

Separate (decoupled) rotor flux control represents the original vector control method. [4]

Now from (8.41) and (8.40),

$$\underline{I}_s = \frac{\underline{\Psi}'_r}{L_{lm}} + js\omega_l \frac{L'_r}{R'_r} \cdot \frac{\underline{\Psi}'_r}{L_{lm}}; T_r = L'_r / R'_r \quad (8.43)$$

or, with Ψ'_r along real axis,

$$\underline{I}_s = I_M + jI_T; I_M = \Psi_r / L_{lm}; I_T = js\omega_l T_r \cdot I_M \quad (8.44)$$

Equations (8.43) and (8.44) show that the stator current may be decomposed into two separate components, one, I_M in phase with rotor flux $\underline{\Psi}_r$ called flux current, and the other, shifted ahead 90° , I_T , called the torque current.

With (8.43) and (8.44), the torque equation (8.42) may be progressively written as

$$T_e = 3p_1 \frac{L_{1m}^2}{L'_r} \cdot I_M \cdot I_T = \frac{3p_1 \Psi_r'^2 S \omega_1}{R'_r} \quad (8.45)$$

Consequently, for constant rotor flux, the torque/speed curve represents a straight line for a separately excited d.c. motor (Figure 8.16).

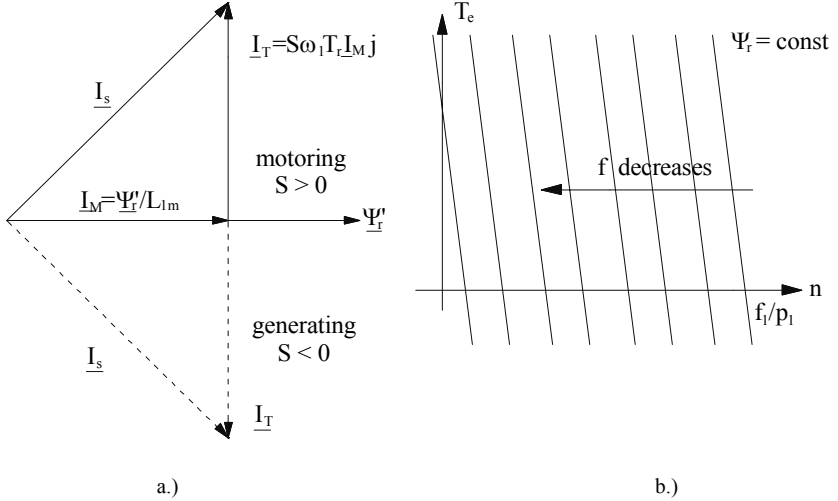


Figure 8.16 Rotor flux vector control: a) stator current components; b) torque versus speed curves for variable frequency f_1 at constant rotor flux

As expected, keeping the rotor flux amplitude constant is feasible until the voltage ceiling in the frequency converter is reached. This happens above the base frequency f_{1b} . Above f_{1b} , Ψ_r has to be decreased, as the voltage is constant. Consequently, a kind of flux weakening occurs as in d.c. motors.

The IM torque-speed curve degenerates into V/f torque/speed curves above base speed.

As long as the rotor flux transients are kept at zero, even during machine transients, the torque expression (8.45) and rotor Equation (8.40) remain valid. This explains the fastest torque response claims with rotor flux vector control. The bonus is that for constant rotor flux the mathematics to handle the control is the simplest. This explains enormous commercial success.

A basic structural diagram for a rotor flux vector control is shown on Figure 8.17.

The rotor flux and torque reference values are used to calculate the flux and torque current components I_M and I_T as amplitudes. Then the slip frequency ($S\omega_1$) is calculated and added to the measured (or calculated on line) speed value ω_r to produce the primary reference frequency ω_1^* . Its integral is the angle θ_1 of rotor flux position. With I_M , I_T , θ_1 the three phase reference currents i_a^* , i_b^* , i_c^* are calculated.

Then a.c. current controllers are used to produce a pulse width modulation (PWM) strategy in the frequency converter to copy the reference currents. There

are some delays in this “copying” process but they are small, so fast response in torque is provided.

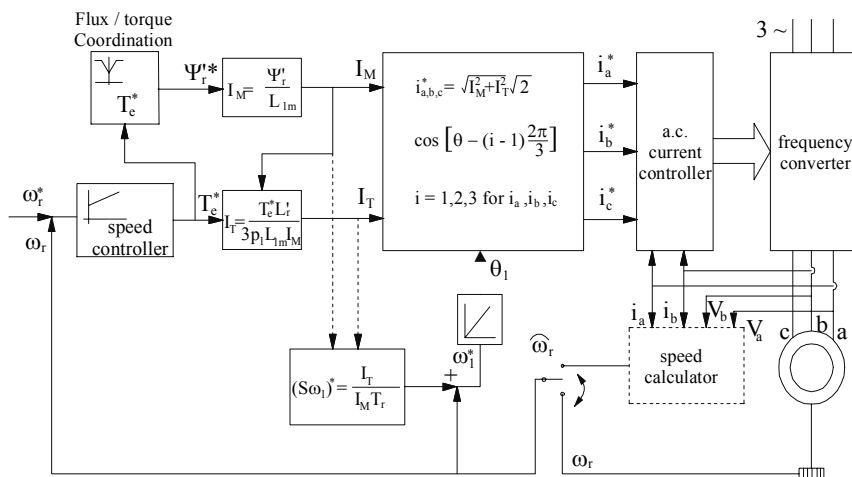


Figure 8.17 Basic rotor flux vector control system

Three remarks are in order.

- to produce regenerative braking it is sufficient to reduce the reference speed ω_r^* below ω_r ; I_T will become negative and so will be the torque
- The calculation of slip frequency is heavily dependent on rotor resistance (T_r) variation with temperature.
- For low speed, good performance, the rotor resistance has to be corrected on line.

Example 8.3 Rotor flux vector speed control

For the induction motor in example 8.2 with the data $2p_1 = 4$, $R_s = R_r = 0.4316 \Omega$, $L_{sl} = L'_{rl} = \frac{X_{sc}}{2 \cdot 2\pi \cdot f_{lb}} = \frac{1.8}{2 \cdot 2\pi \cdot 50} = 2.866 \cdot 10^{-3} \text{ H}$,

and $L_{1m} \approx \frac{V_s}{I_{0m} \cdot 2\pi \cdot f_{lb}} - L_{sl} = \frac{220}{18.37 \cdot 0.3 \cdot 314} - 2.866 \times 10^{-3} = 0.12427 \text{ H}$, the

rotor flux magnetizing current $I_M = 6 \text{ A}$ and the torque current $I_T = 20 \text{ A}$.

For speed $n = 600 \text{ rpm}$, calculate the torque, rotor flux Ψ_r , stator flux slip frequency $S\omega_1$, frequency ω_1 , and voltage required.

Solution

The rotor flux Ψ'_r (8.44) is

$$\Psi'_r = L_{1m} \cdot I_M = 0.12427 \cdot 6 = 0.74256 \text{ Wb}$$

Equation (8.45) yields

$$T_e = 3p_1 \frac{L_{lm}^2}{L_r'} I_M \cdot I_T = 3 \cdot 2 \cdot \frac{0.12427^2}{2.866 \times 10^{-3} + 0.12427} \cdot 6 \times 20 = 87.1626 \text{ Nm}$$

The slip frequency is calculated from (8.44)

$$S\omega_1 = \frac{1}{T_r} \frac{I_T}{I_M} = \frac{20}{6} \cdot \frac{0.4316}{0.12417 + 2.866 \times 10^{-3}} = 11.30 \text{ rad/s}$$

Now the frequency ω_1 is

$$\omega_1 = 2\pi n \cdot p_1 + S\omega_1 = 2\pi \cdot \frac{600}{60} \cdot 2 + 11.30 = 136.9 \text{ rad/s}$$

To calculate the voltage, we have to use Equations. (8.40) and (8.41) progressively.

$$\underline{\Psi}_s = \frac{L_{lm}}{L_r'} \cdot L_{lm} I_M + L_{sc} \cdot (I_M + jI_T) = L_s I_M + jL_{sc} I_T \quad (8.46)$$

So the stator flux has two components, one produced by I_M through the no-load inductance $L_s = L_{sl} + L_{lm}$ and the other produced by the torque current through the shortcircuit inductance L_{sc} .

$$\underline{\Psi}_s = (2.866 \times 10^{-3} + 0.12427) \cdot 6 + j \cdot 2 \cdot 2.866 \times 10^{-3} \cdot 20 = 0.7628 + j \cdot 0.11464 \quad (8.47)$$

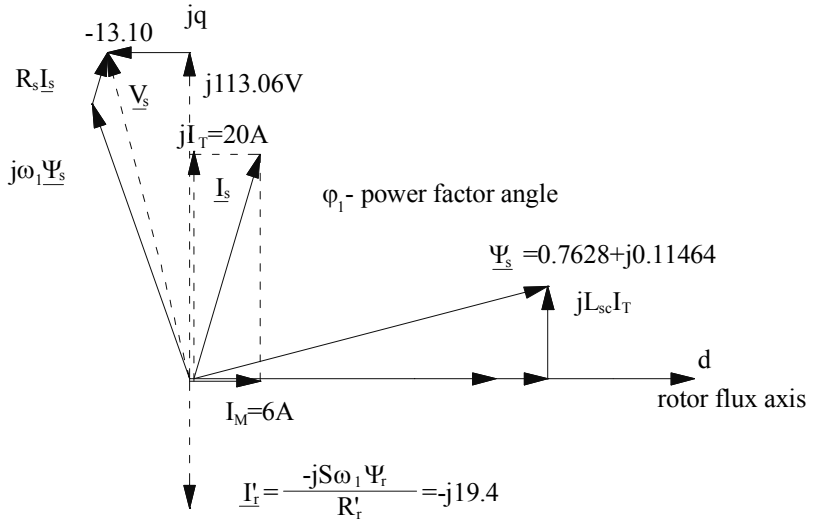


Figure 8.18 Phasor diagram with rotor and stator fluxes shown

The results in terms of fluxes and voltage are summarized in [Figure 8.18](#)

For negative torque (regenerative braking) only I_T becomes negative and so does the slip frequency $S\omega_1$.

Now from (8.40):

$$\underline{V}_s = j\omega_1 \underline{\Psi}_s + \underline{I}_s R_s = j \cdot 136.9 \cdot (0.7628 + j \cdot 0.11464) + (6 + j \cdot 20) \cdot 0.4316 = -13.10 + j \cdot 113.06$$

$$V_s = \sqrt{13.10^2 + 113.06^2} = 113.81 \text{ V}$$

Let us further exploit the torque expression T_e which may be alternative to (8.42).

$$T_e = 3p_1 \operatorname{Re}(j\underline{\Psi}_s \underline{I}_s^*) = 3p_1 (L_s - L_{sc}) I_M \cdot I_T \quad (8.48)$$

Also the rotor current (8.38) is

$$I_r' = S\omega_1 \frac{L_{lm} I_M}{R_r'} \quad (8.49)$$

Torque Equation (8.48) may be interpreted as pertaining to a reluctance synchronous motor with constant high magnetic saliency as $L_s/L_{sc} > 10 - 20$ in general.

This is true only for constant rotor flux.

The apparent magnetic saliency is created by the rotor current I_r' which is opposite to jI_T in the stator (Figure 8.18) to kill the flux in the rotor along axis q . The situation is similar to the short-circuited secondary effect on the transformer equivalent inductance.

Stator flux vector control may be treated in a similar way. For detailed information on advanced IM drives see References [5,6].

8.5 SPEED CONTROL METHODS FOR WOUND ROTOR IMs

When the rotor of IMs is provided with a wound rotor, speed control is performed by

- Adding a variable resistor to the rotor circuit
- Connecting a power converter to the rotor to introduce or extract power from the rotor. Let us call this procedure additional voltage to the rotor.

As the method of additional rotor resistance has been presented for starting, it will suffice to stress here that only for limited speed control range (say 10%) and medium power such a method is still used in some special applications. In the configuration of self-adjustable resistance, it may also be used for 10 to 15% speed variation range in generators for windpower conversion systems.

In general, for this method, a unidirectional or a bidirectional power flow frequency converter is connected to the rotor brushes while the stator winding is fed directly, through a power switch, to the power grid (Figure 8.19).

Large power motors (2-3 MW to 15 MW) or very large power generators/motors, for pump-back hydropower plants (in the hundreds of MW/unit), are typical for this method.

A half-controlled rectifier-current source inverter has constituted for a long while one of the most convenient ways to extract energy from the rotor while the speed decreases 75 to 80% of its rated value. Such a drive is called a slip recovery drive and it may work only below ideal no-load speed ($S > 0$).

8.5.1 Additional voltage to the rotor (the doubly-fed machine)

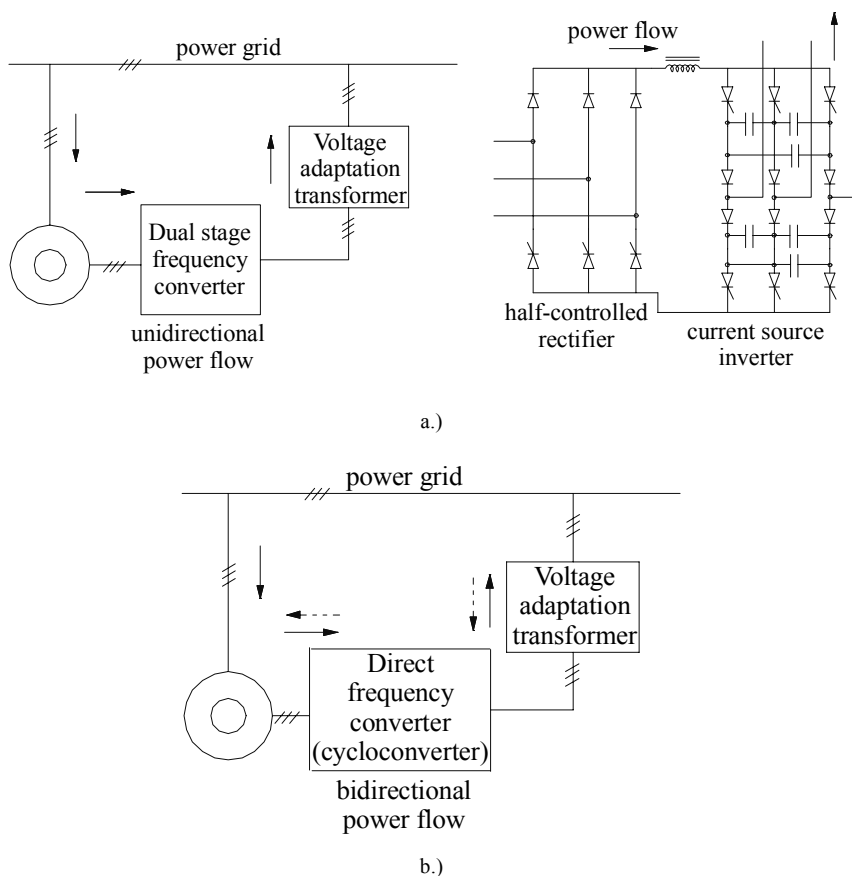


Figure 8.19 Additional voltage to the rotor
a.) with unidirectional power flow; b.) with bidirectional power flow

On the other hand, with bidirectional power flow, when the phase sequence of the voltages in the rotor may be changed, the machine may work both as a motor or as a generator, both below and above ideal no-load speed f_1/p_1 .

With such direct frequency converters, it is possible to keep the rotor slip frequency f_2 constant and adjust the rotor voltage phase angle δ with respect to stator voltage after reduction to stator frequency.

The speed is constant under steady state and the machine behaves like a synchronous machine with the torque dependent on the power angle δ ($S = f_2/f_1 = \text{ct}$).

On the other hand, the frequency f_2 may be varied with speed such that

$$f_2 = f_1 - np_1; \quad s = f_2 / f_1 - \text{variable} \quad (8.50)$$

In this case, the phase angle δ may be kept constant.

The rotor equation is

$$\underline{I}'_r \frac{R'_r}{s} + \underline{V}'_r = -jS\omega_1 \underline{\Psi}'_r = S \underline{E}'_r \quad (8.51)$$

For $\underline{V}'_r$ in phase (or in phase opposition for $V'_r < 0$) with $\underline{E}'_r$

$$\underline{I}'_r R'_r = S \underline{E}'_r - \underline{V}'_r \quad (8.52)$$

For zero rotor current, the torque is zero. This corresponds to the ideal no-load speed (slip, S_0)

$$s_0 E'_r - V'_r = 0; \quad s_0 = \frac{V'_r}{E'_r} \quad (8.53)$$

So, may be positive if $V'_r > 0$, that is $\underline{V}'_r$ and $\underline{E}'_r$ are in phase while it is negative for $V'_r < 0$ or V'_r or $\underline{V}'_r$ and $\underline{E}'_r$ in phase opposition.

For constant values of V'_r (+ or -), the torque speed curves obtained by solving the equivalent circuit may be calculated as

$$T_e = \frac{P_{elm} p_1}{S \omega_1} = \frac{3 p_1}{S \omega_1} \left[I'^2_r R'_r + V'_r I'_r \cos \theta'_r \right] \quad (8.54)$$

θ'_r is the angle between $\underline{V}'_r$ and $\underline{I}'_r$. In our case, $\theta_r = 0$ and V'_r is positive or negative, and given.

It is seen (Figure 8.20) that with such a converter, the machine works well as a motor above synchronous conventional speed f_1 / p_1 and as a generator below f_1 / p . This is true for voltage control. A different behavior is obtained for constant rotor current control. [7]

However, under subsynchronous motor and generator modes, all are feasible with adequate control.

Example 8.4 Doubly - fed IM

An IM with wound rotor has the data: $V_{sn} = 220$ V/phase, $f_1 = 50$ Hz, $R_s = R'_s = 0.01 \Omega$, $X_{sl} = X'_{rl} = 0.03 \Omega$, $X_{lm} = 2.5 \Omega$, $2p_1 = 2$, $V_m = 300$ V/phase, $S_n = 0.01$. Calculate

- the stator current and torque at $s_n = 0.01$ for the short-circuited rotor;
- for same stator current at $n = 1200$ rpm calculate the rotor voltage V_r in phase with stator voltage V_{sn} (Figure 8.21) and the power extracted from the rotor by frequency converter.

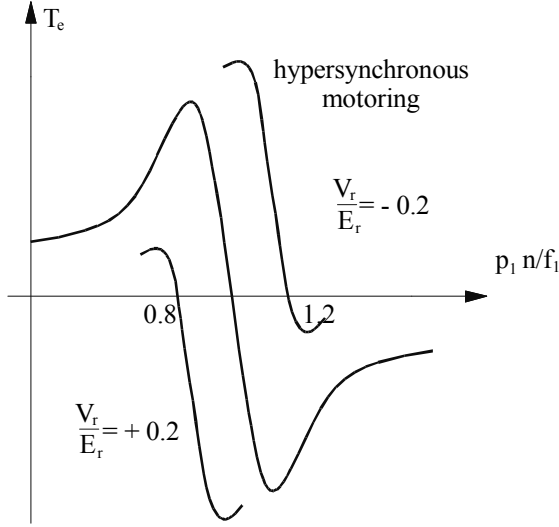


Figure 8.20 Torque speed curves for $V_r/E_r = \pm 0.2$, $\theta'_r = 0$

Solution

The stator current (see chapter 7) is

$$\begin{aligned} (I'_s)_{V'_r=0} &\approx \frac{V_s}{\sqrt{\left(R_s + C_1 \frac{R'_r}{s}\right)^2 + (X_{ls} + C_1 X'_{ri})^2}} = \\ &= \frac{220}{\sqrt{\left(0.01 + 1.012 \frac{0.01}{0.01}\right)^2 + (0.03 + 1.012 \cdot 0.03)^2}} = 217.17 \text{ A} \end{aligned}$$

with

$$C_1 = \frac{X_{ls}}{X_{lm}} + 1 = 1 + \frac{0.03}{2.5} = 1.012 \quad (8.55)$$

The actual rotor current I_r per phase is

$$I_r = I'_r \cdot \frac{V_s}{V_{rn}} = 217.17 \cdot \frac{220}{300} \approx 152 \text{ A} \quad (8.56)$$

The torque T_e is

$$T_e = \frac{3 R'_r I_r^2}{s \omega_1} \cdot p_1 = \frac{3 \cdot 0.01 \cdot 217.172}{0.01 \cdot 2\pi \cdot 50} = 450.60 \text{ Nm} \quad (8.57)$$

If $\underline{V}_r$ is in phase with $\underline{V}_{sn}$, then

$$\begin{aligned}
 (\underline{I}'_r)_{S'} &\approx I_s = \frac{V_s + V'_r/S'}{\sqrt{\left(R_s + C_1 \frac{R'_r}{S'}\right)^2 + (X_{sl} + C_1 X'_{rl})^2}} = \\
 &= \frac{220 + V'_r/0.2}{\sqrt{\left(0.01 + 1.012 \frac{0.01}{0.2}\right)^2 + (0.03 + 1.012 \cdot 0.03)^2}} = 217.17
 \end{aligned} \tag{8.58}$$

$$S' = 1 - \frac{np_1}{f_1} = 1 - \frac{1200}{60} \cdot \frac{2}{50} = 0.2; f_2 = S' f_1 = 0.2 \cdot 50 = 10 \text{ Hz}$$

So $V'_r = -40.285 \text{ V}$

In this case the angle between $\underline{V}'_r$ and $\underline{I}'_r$ corresponds to the angle $+ \underline{V}'_s$ and $- \underline{I}'_s$ (from 8.58)

$$\theta'_r (\underline{V}'_r, \underline{I}'_r) \approx -45^\circ + 180^\circ = 135^\circ \tag{8.59}$$

Now the torque (8.54) is

$$T_e = \frac{3 \cdot 2}{0.2 \cdot 2\pi \cdot 50} [0.01 \cdot 217.17^2 + (-40.28)(217.17)(-0.707)] = 635.94 \text{ Nm} \tag{8.60}$$

Note that the new torque is larger than for $S = 0.01$ with the short-circuited rotor.

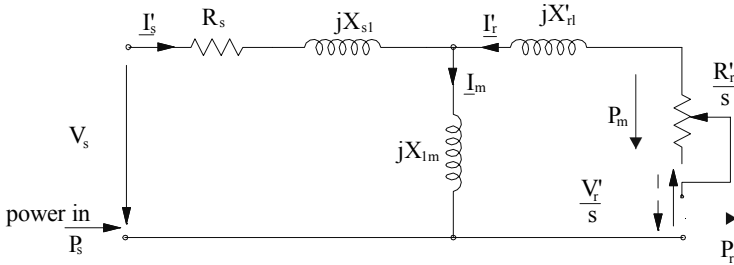


Figure 8.21 Equivalent circuit with additional rotor voltage $\underline{V}'_r$

The input active power P_s , electric power out of rotor P_r and mechanical power P_m are

$$\begin{aligned}
 P_s &= 3V_s I_s \cos \phi_s = 3 \cdot 220 \times 217.17 \times 0.707 = 101.335 \times 10^3 \text{ W} \\
 P_r &= 3V_r I_r \cos \theta_1 = 3 \cdot 40.38 \times 217.17 \cdot 0.707 \approx 18.6 \times 10^3 \text{ W} \\
 P_m &= T_e \cdot 2\pi n = 635.94 \cdot 2\pi \cdot 1200/60 = 79.874 \times 10^3 \text{ W}
 \end{aligned} \tag{8.61}$$

The efficiency at 1200 rpm η is

$$\eta = \frac{P_m}{P_s - P_r} = \frac{79.874}{101.335 - 18.6} = 0.9654 \quad (8.62)$$

Note that core, mechanical, and stray load losses have been neglected.

$$-j\omega_1 \underline{\Psi}_r = -\left(\frac{L'_r}{L_{lm}} \cdot \underline{\Psi}_s - L_{sc} \underline{I}_s \right) j\omega_1 = -\frac{L'_r}{L_{lm}} [(V_s - R_s \underline{I}_s) - jX_{sc} \underline{I}_s] = \underline{E}'_r \quad (8.63)$$

$$\begin{aligned} \underline{E}'_r &= -\frac{(2.5 + j0.03)}{2.5} [220 - (217.17 - j217.17)0.707(0.01 + j0.06036)] \\ &= -(209.49 - j7.74) \end{aligned} \quad (8.64)$$

Now $\underline{I}'_r$ is recalculated from (8.51)

$$\underline{I}'_r = \frac{\underline{SE}'_r - \underline{V}'_r}{R'_r} = \frac{-0.2(211.767 - j7.74) - (-40.301)}{0.01} = (-158.88 + j154.8) = -\underline{I}_s \quad (8.65)$$

Both components of $\underline{I}'_r$ are close to those of (8.58).

When the rotor slip frequency f_2 is constant, the speed is constant so only the rotor voltage sequence, amplitude, and phase may be modified.

The phase sequence information is contained into S_2 sign:

$$S_2 = f_2 / f_1 > 0 \quad (8.66)$$

We may calculate the stator current $\underline{I}_s$ and the rotor current $\underline{I}'_r$ (reduced to the stator) from the equivalent circuit (Figure 8.21) is:

$$\underline{I}_s = \frac{\underline{V}_s (R'_r / s + jX'_r) - jX_{lm} \underline{V}'_r / s}{(R_s + jX_s)(R'_r / s + jX'_r) + X_{lm}^2}; \underline{X}_s = X_{sl} + X_{lm} \quad (8.67)$$

$$\underline{I}'_r = \frac{\underline{V}'_r (R_s + jX_s) / s - jX_{lm} \underline{V}_s}{(R_s + jX_s)(R'_r / s + jX'_r) + X_{lm}^2}; X'_r = X'_{lr} + X_{lm} \quad (8.68)$$

The stator and rotor power input powers are

$$\begin{aligned} P_s &= 3 \operatorname{Re}(\underline{V}_s \underline{I}_s^*); T_e \approx (P_s - 3R_s \underline{I}_s^2) \frac{P_1}{\omega_1} \\ Q_s &= 3 \operatorname{Im}(\underline{V}_s \underline{I}_s^*) \end{aligned} \quad (8.69)$$

Similarly the powers out of rotor are

$$\begin{aligned} P_r &= 3 \operatorname{Re}(\underline{V}'_r \underline{I}'_r^*) \\ Q_r &= 3 \operatorname{Im}(\underline{V}'_r \underline{I}'_r^*) \end{aligned} \quad (8.70)$$

With $S = \text{const}$, such a control method can work at constant rotor voltage V'_r but with variable phase γ (V_s, V'_r). Alternatively, it may operate at constant stator or rotor current [8,9]. Finally, vector control is also feasible. [6] Such schemes are currently proposed for powers up to 300 MW in pump-storage power plants where, both for pumping and for generating, a 10 to 25% of speed control improves the hydroturbine-pump output.

The main advantage is the limited rating of the rotor-side frequency converter $S_r = S_{\max} \cdot S_n$. As long as $S_{\max} < 0.2 - 0.15$, the savings in converter costs are very good. Notice that resistive starting is required in such cases.

For medium and lower power limited speed control, dual stator winding stator nest cage rotor induction motors have been proposed. The two windings have different pole numbers p_1, p_2 , and the rotor has a pole count $p_r = p_1 + p_2$. One winding is fed from the power grid at the frequency f_1 and the other at frequency f_2 from a limited power frequency converter. The machine speed n is

$$n = \frac{f_1 \pm f_2}{p_1 + p_2} \quad (8.71)$$

The smaller f_2 , the smaller the rating of the corresponding frequency converter. The behavior is typical to that of a synchronous machine when f_2 is const. Low speed applications such as wind generators or some pump applications with low initial cost for very limited speed control range (less than 20%) might be suitable for those configurations with rather large rotor losses.

8.6 SUMMARY

- Starting methods are related to IMs fed from the industrial power grid.
- With direct starting and stiff local power grids, the starting current is in the interval of 580 to 650% (even higher for high efficiency motors).
- For direct starting at no mechanical load, the rotor winding energy losses during machine acceleration equals the rotor-attached kinetic energy at no load.
- For direct frequent starting at no load, and same stator, rotors with higher rotor resistance lead to lower total energy input for acceleration.
- To avoid notable voltage sags during direct starting of a newly installed IM, the local transformer KVA has to be oversized accordingly.
- For light load, starting voltage reduction methods are used, as they reduce the line currents. However, the torque/current ratio is also reduced.
- Voltage reduction is performed through an autotransformer, wye/delta connection, or through softstarters.
- Softstarters are now built to about 1MW motors at reasonable costs as they are made with thyristors. Input current harmonics and motor additional losses are the main drawbacks of softstarters. However, they are continually being improved and are expected to be common practice in light load starting applications (pumps, fans) where speed

control is not required but soft (low current), slow but controlled, starting are required.

- Rotor resistive starting of wound rotor IMs is traditional. The method produces up to peak torque at start, but at the expense of very large additional losses.
- Self adjustable resistance-reactance paralleled pairs may also be used for the scope to cut the cost of controls.
- Speed control in cage rotor IMs may be approached by voltage amplitude control, for a very limited range (up to 10 to 15%, in general).
- Pole changing windings in the stator can produce two speed motors and are used in some applications, especially for low power levels.
- Dual stator windings and cage rotors can also produce two speed operations efficiently if the power level for one speed is much smaller than for the other.
- Coordinated frequency/voltage speed control represents the modern solution to adjustable speed drives.
- V/f scalar control is characterized by an almost linear dependence of voltage amplitude on frequency; a voltage boost $V_0 = (V)_{f1} = 0$ is required to produce sufficient torque at lowest frequency $f_1 \approx 3$ Hz. Slip feedforward compensation is added. Still slow transient response is obtained. For pumps, fans, etc., such a method is adequate. This explains its important market share.
- Rotor flux vector control keeps the rotor flux amplitude constant and requires the motor to produce two stator current components: a flux current I_M and a torque current I_T , 90° apart. These two components are decoupled to be controlled separately. Fast dynamics, quick torque availability, stable, high performance drives are built and sold based on rotor flux vector control or on other related forms of decoupled flux and torque control.
- Linear torque/speed curves, ideal for control, are obtained.
- Flux, torque coordination through various optimization criteria could be applied to cut energy losses or widen the torque-speed range.
- For constant rotor flux, the IM behaves like a high saliency reluctance synchronous motor. However, the apparent saliency is produced by the rotor currents phase- shifted by 90° with respect to rotor flux for cage rotors. As for the reluctance synchronous motor, a maximum power factor for the loss, less motor can be defined as

$$\cos \varphi_{\max} = \frac{1 - L_{sc} / L_s}{1 + L_{sc} / L_s}; L_s / L_{sc} > 15 \div 20 \quad (8.72)$$

L_s – no-load inductance; L_{sc} – short-circuit inductance.

- Wound rotor speed control is to be approached through frequency converters connected to the rotor brushes. The rotor converter rating is low. Considerable converter cost saving is obtained with limited speed

control so characteristic to such drives. With adequate frequency converter, motoring and generating over or under conventional synchronous speed ($n_1 = f_1/p_1$) is possible. High and very high power motor/generator systems are main applications as separated active and reactive power control for limited speed variation at constant frequency is feasible. In fact, the largest electric motor with no-load starting has been built for such purposes (for pump storage power plants).

- Details on control of electric drives with IMs are to be found in the rich literature dedicated to this very dynamic field of engineering.

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